INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS
Int. J. Commun. Syst. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/dac.1280

Clustering-based power-controlled routing for mobile wireless sensor networks

Atta ur Rehman Khan[1], Sajjad A. Madani[1], Khizar Hayat[1,*,†] and Samee Ullah Khan[2]

[1]*Computer Science Department, COMSATS Institute of Information Technology, Abbottabad, Pakistan*
[2]*Department of Electrical and Computer Engineering, North Dakota State University, Fargo, ND 58108-6050, U.S.A.*

SUMMARY

This paper presents two new routing protocols for mobile sensor networks, viz. power-controlled routing (PCR) and its enhanced version, i.e. enhanced power-controlled routing (EPCR). In both the protocols, fixed transmission power is employed in the clustering phase but when ordinary nodes are about to send their data to their respective cluster-heads, they change their transmission power according to their distance from their cluster-head. While in PCR, the nodes are associated with the cluster-head on the basis of weight, in EPCR it is done on the basis of distance. In addition to the protocols, we are suggesting a packet loss recovery mechanism for the PCR and EPCR. Both protocols work well for both mobile and static networks and are designed to achieve high network lifetime, high packet delivery ratio, and high network throughput. These protocols are extensively simulated using mass mobility model, with different speeds and different number of nodes to evaluate their performance. Simulation results show that both PCR and EPCR are successful in achieving their objectives by using variable transmission powers and smart clustering. Copyright © 2011 John Wiley & Sons, Ltd.

Received 14 January 2011; Revised 7 March 2011; Accepted 20 March 2011

KEY WORDS: clustering; variable transmission power; mobile sensor networks; distributed routing protocol

1. INTRODUCTION

Energy has always been a critical issue in wireless sensor networks (WSNs) because sensor nodes are usually deployed in an environment where replacement of batteries is not only costly but also laborious. WSNs are mainly handicapped by the energy consumption due to both transmission and reception powers of the underlying sensor nodes. The simplicity of 802.11 notwithstanding its fixed transmission power consumption leads to wastage of considerable network throughput [1, 2]. With *ad hoc* WSNs, control of transmission power consumption is thus quintessential for two obvious reasons, namely the avoidance of battery power wastage and enhanced throughput [3]. While dealing with WSNs, a fair number of researchers have kept energy consumption as their primary goal while treating the network throughput as a secondary issue [4, 5]. Other things apart, using variable transmission powers can lead to both increased network lifetime and throughput [1, 6]. As far as network topology is concerned, clustering-based sensor networks have shown better results in terms of network throughput and energy consumption [7, 8] but they are limited by the fact that the nodes consume constant transmission power independent of their distance

*Correspondence to: Khizar Hayat, Computer Science Department, COMSATS Institute of Information Technology, Abbottabad, Pakistan.
†E-mail: khizarhayat@ciit.net.pk

from the cluster-head which not only results in energy wastage but also decreases network throughput.

In the light of the aforementioned points, we are proposing two new protocols with power economy being the main thrust. In the first one, which will be hereafter called the power-controlled routing (PCR), fixed transmission power will be used in the clustering phase and when normal nodes are about to send their data to their respective cluster-heads, they change their transmission power according to their distance from their cluster-head. The selection criterion for node association, in PCR, is weight based which may result in some problems, especially when a node not only lies on the border of the transmission range of the potential cluster-head but also in the transmission range of more than one cluster-head. For such a node, there is a high probability to go out of the transmission range of a cluster-head that was selected on the basis of weight. To cater for problems like these, we have extended this criterion to include the distance too and hence the second protocol, the enhanced power-controlled routing (EPCR). Thus, in PCR the nodes are associated with the cluster-head on the basis of weight, whereas in EPCR it is done on the basis of distance. We are also suggesting a packet loss recovery mechanism for the proposed protocols to avoid extra rebroadcast, as is the case with the distributed efficient multi-hop clustering (DEMC).

The remainder of the paper is organized as follows. Section 2 gives a brief overview of the related work from the literature. The proposed protocols along with a recovery mechanisms are elaborated in Section 3. Section 4 illustrates the results of the simulations, carried out for the sake of proving the effectiveness of our solutions, while Section 5 sums up the paper.

2. RELATED WORK

Hierarchical routing protocols have been widely investigated for sensor networks [9–11]. In such schemes, the sensing region is divided into small regions called clusters. Every cluster has a cluster-head and all nodes within a cluster are associated with the cluster-head. Each node sends its data to the cluster-head whose main job is to perform aggregation and forward the processed data to the sink afterwards. Some of the popular hierarchal protocols are the low-energy adaptive clustering hierarchy (LEACH), the hybrid energy-efficient distributed (HEED), the distributed efficient clustering approach (DECA) and the DEMC.

The main idea behind LEACH [9] is to form clusters of the sensor nodes based on the received signal strength indicator (RSSI) and use cluster-heads for routing data toward the sink. This technique is more energy efficient because only selected cluster-heads perform the routing. To avoid sending duplicate packets, the cluster-heads perform the additional job of data aggregation and data fusion. However, LEACH changes cluster-heads randomly from time to time and assumes that the nodes are static. Another drawback of LEACH is its limited geographic scalability which is due to its unwarranted assumption that the nodes can directly send their data to the sink. Power-efficient Gathering in Sensor Information Systems (PEGASIS) [11] is an enhanced form of the LEACH protocol. The difference between LEACH and PEGASIS is that, instead of forming clusters PEGASIS forms chains. The transmission takes place between neighbor nodes and only one node is selected to communicate with base-station/sink. Data are transmitted from node to node and aggregated at each node and then finally transmitted to base-station. PEGASIS uses greedy method to form a chain.

Table-less position-based routing (TPR) [12] is one of the mature protocols that deals with dead end problem by recovery and supports mobility as well. TPR also supports delay-energy-aware metric to adjust end-to-end delay according to the situation and extends network lifetime. Owing to zero table maintenance cost, TPR has a propensity to be more scalable and efficient. Energy-aware routing for cluster-based sensor networks (EARCS) [8] is a protocol that proposes a three-tier hierarchical routing architecture. In this protocol, the cluster-head is used as a gateway with the assumption that there is no energy constraint on the gateway. Moreover, the gateway knows the location of all the other sensor nodes and can change their operation modes. The four major

DOI: 10.1002/dac

operation modes used by this protocol are sensing only mode, relaying only mode, sensing-relaying mode and inactive mode.

Energy-efficient clustering scheme (EECS) [13] protocol is based on the assumption that all the cluster-heads can directly communicate with the base-station. In EECS clusters are of variable size in a way that clusters closer to the base-station are larger in size compared to the clusters far from the base-station. This technique proved to be efficient for saving energy in intra-cluster communication and improved network lifetime. A related work by the same authors is the energy-efficient unequal clustering mechanism (EEUC) [14]. This mechanism is also based on unequal cluster sizing for uniform energy consumption in the network. The main drawback of this protocol is the probabilistic selection of the cluster-head. Moreover, it does not guarantee the fact that every node would be a part of the cluster. Therefore, a few nodes may be left without being part of any cluster.

HEED [15] is a distributed clustering protocol and unlike LEACH it does not select cluster-heads randomly but takes into account the residual energy of nodes as well as intra-cluster communication cost in selecting the cluster-heads leading to extended network lifetime. The problems with HEED are its suitability limited only to static networks and the employment of complex probabilistic methods and multiple clustering messages per node for the selection of cluster-head.

DECA [16] is one of the energy-efficient clustering protocols that considers the mobility of sensor nodes. DECA bears similarity to HEED [15] and another algorithm given in [10]. However, DECA differs from these two in score calculation to nominate the cluster-head that is based on three parameters, viz. node residual energy, connectivity, and a unique node identifier. Each node sends a periodic 'hello' message bearing its identity via which the neighbor lists are constructed. Compared to LEACH and HEED, DECA is a simpler algorithm because it does not use any complex probabilistic methods for cluster-head selection. It is also energy efficient as it sends only one message per node for cluster-head selection, unlike HEED that sends two to three messages per node. Neighbor list maintenance is, however, an overhead and requires processing power, memory and extra communication. Another problem with DECA is the high possibility of wrong cluster-head selection which may lead to packet losses, as all the packets sent by nodes will ultimately be discarded. Moreover, the mobile nature of the network requires the connectivity among cluster-heads to be ensured—otherwise the lack of communication among cluster-heads, without any specified recovery mechanism may lead to loss of information on the part of the unconnected clusters.

DEMC [17] addresses most of the drawbacks of the DECA protocol, because the former adopts different scoring (weight) calculation and clustering mechanisms. The frequency of clustering messages is far less with DEMC as it sends only one message per cluster, for initial clustering, instead of sending one message per node (DECA) or even more in the cases of HEED and LEACH. In addition, DEMC also avoids wrong cluster-head selection, thus leading to improved packet delivery ratio. Limitations of DEMC include (a) fixed transmission power throughout the span of network lifetime, (b) fixed cluster operation time independent of nodes' movement speeds, and (c) less energy-efficient packet loss recovery mechanism.

3. THE PROPOSED PROTOCOLS

A WSN can be modeled as a set of nodes denoted by V, where each node $v \in V$ is identified by a unique identifier. The nodes are interconnected by full-duplex wireless communication links. Since the network is mobile, the nodes may change their positions from time to time without any notice. The clustering problem is defined as the selection of cluster-heads, from V, enough in number to completely cover the network. Thus, the nodes in V are partitioned into disjoint clusters, i.e. a node $v \in V$ can be a part of only one cluster at a time. After clustering, a node can communicate directly only with its cluster-head. The clustering protocol must work in a distributed fashion, allowing all nodes to make their decisions independently based on local information. Moreover, clustering should be fast, less complicated, and efficient in terms of the number of messages. Furthermore,

DOI: 10.1002/dac

the clustering algorithm should be energy efficient, use variable transmission power, and adaptable to moderate mobility. We are making the following assumptions for our network model:

1. Sensor nodes are mobile complacent with the mass mobility model.
2. Nodes will be using fixed transmission power all the time except when a node sends its data to its cluster-head.
3. The base-station is static.
4. Nodes are location-unaware and do not have any GPS modules.
5. All nodes are homogeneous with respect to the architecture and use of resources.
6. Nodes are left unattended after deployment.

For the sake of convention we are characterizing three types of nodes in this work.

- *Cluster-heads*: The nodes responsible for gathering data from ordinary nodes.
- *Guard nodes*: The nodes lying in the transmission range of more than one cluster-head.
- *Normal nodes*: All those nodes that lie in the transmission range of a single cluster-head.

3.1. The PCR protocol

Based on the DEMC protocol, we are proposing the PCR. The PCR protocol is significantly different from DEMC in terms of transmission power, cluster operation time, and recovery mechanism. DEMC uses fixed transmission power in the entirety of the network lifetime without any change, whereas PCR uses variable transmission power. In PCR, however, fixed transmission power is used in the clustering phase and when normal nodes are about to send their data to the cluster-head, they change their transmission power according to their distance from the cluster-head. PCR does not employ any GPS component to determine the distance of node from the cluster-head. Distance of a node from the cluster-head is determined on the basis of RSSI.

Some researchers state that variable transmission power is harmful and reduced signal strengths in meshed networks reduce their capacity [18]. This may be due to the fact that with low signal strengths, packet transmission delay will escalate. But for the following reasons, we believe that variable transmission power will not affect the performance of our proposed protocols:

1. As compared to the sensor networks, with meshed networks on one hand, the data transfer rate is very high and on the other, the transmission duration is long.
2. With our protocols the transmission power is constant during the phases of clustering, inter-cluster communication, and recovery. It is when the nodes are sending their data to cluster-heads that variable transmission power is employed.
3. Since we would have more than one cluster and all nodes are mobile, think of a scenario when all nodes will be transmitting will full power. In that eventuality, they will also affect nodes in the neighboring clusters.

With these reasons we came to the conclusion that reducing transmission power in cluster-based networks will not lead to a considerable reduction in network capacity but will, instead, result in increased network throughput and minimized energy consumption.

3.1.1. PCR cluster formation. Similar to HEED, DECA and DEMC, the PCR first calculates its weight. The weight is calculated on the basis of node residual energy (E) and node identifier (I), as shown below:

$$\text{weight} = \alpha \times E + \beta \times I, \tag{1}$$

In other words ‘weight’ is a linear combination of E and I. E is having greater proportion in weight calculation, in comparison to I, because cluster-head nomination is solely based on E unless a tie occurs in which case I acts as a tie breaker. Hence one can reasonably assume $0<\beta<\alpha<1$. In Equation (1), I acts as a tie breaker if the residual energies of two nodes are equal. After weight

DOI: 10.1002/dac

calculation is done every node sets its timer (delay) for broadcasting clustering message according to the following equation:

$$\text{Timer} = \frac{1}{\text{weight}}. \tag{2}$$

During the initialization phase, every node assumes that it is a cluster-head and sets its cluster-head flag. When the timer expires for any specific node, it broadcasts a message, containing node *ID* and weight, to all its neighbors within its transmission range. The other nodes upon receiving the clustering message, save the received weight along with the RSSI of the received message and the received ID as cluster-head. They then reset their cluster-head flag and cancel scheduled timer for clustering message. If a receiving node is in the range of more than one cluster-heads and a second clustering message is received. The receiving node compares previous weight with the new received weight and if the new weight is better than the previous one, replace the previous weight with the new one; in the case of weight change it saves the received ID as cluster-head.

It must be borne in mind that there is no limit on the number of clusters created during the process because all the nodes are mobile and clustering is dynamic and the numbers of clusters are dependent on nodes deployment, transmission range, area, and number of nodes. The nodes are deployed randomly in our situation. Hence the number of clusters varies from scenario to scenario in mobile networks. Hence, on one extreme, if all nodes move toward a specific corner and are in the transmission range of a single cluster-head then only one cluster will be formed; on the contrary, if the area is too large and we have limited number of nodes and no node is in transmission range of each other, then N clusters will be formed for N nodes. In this latter case, the complexity is high due to large number of clusters; one can argue that the energy can be successfully optimized by the transmission of just small data packets. The problem is, however, that one cannot keep the packet size smaller for all applications as different applications have different requirements. Many applications are data intensive and smaller packets would lead to below par performance. We are, therefore, emphasizing more on variable transmission power rather than small packets of fixed size, in order to minimize energy consumption.

3.1.2. PCR intra-cluster communication. When the clustering phase ends, normal nodes will start sending their acquired information to cluster-heads. To send data to its cluster-head, a node will first check the RSSI value earlier received from the cluster-head message and calculate the estimated distance. Many works can be found in the literature wherein the distance calculation is based on RSSI [19–21]. The equation that we use for distance estimation is as follows [22]:

$$d = 10^{\frac{-(\text{RSSI}+A+\sigma_{\text{offset}})}{10n}}, \tag{3}$$

where n is signal propagation constant, A is the received signal's strength at a distance of 1 m and σ_{offset} is a random value of the measured RSSI which ranges from 0 to 1 dBm. The detailed derivation of the parameter d is given in [23].

Based on the estimated distance, the node will set new transmission power and then transmit data to its cluster-head. Therefore, if the node lies closer to the cluster-head, then there is no need of transmitting with full power as shown in the Figure 1(a).

Reducing transmission power for transmitting data to cluster-head will provide two benefits, namely lower energy consumption and increased network throughput. As shown in Figure 1(b), when A tries to communicate with B using full transmission power, D and C also lies in communication range and while A and B are communicating C and D are unable to communicate. However, when A reduces its transmission range for communication with B, C and D can also communicate with each other. In this way, not only energy consumption is reduced but also network throughput is increased.

When data are received by the cluster-head, it performs data aggregation and forwards the data to the sink via other cluster-heads.

DOI: 10.1002/dac

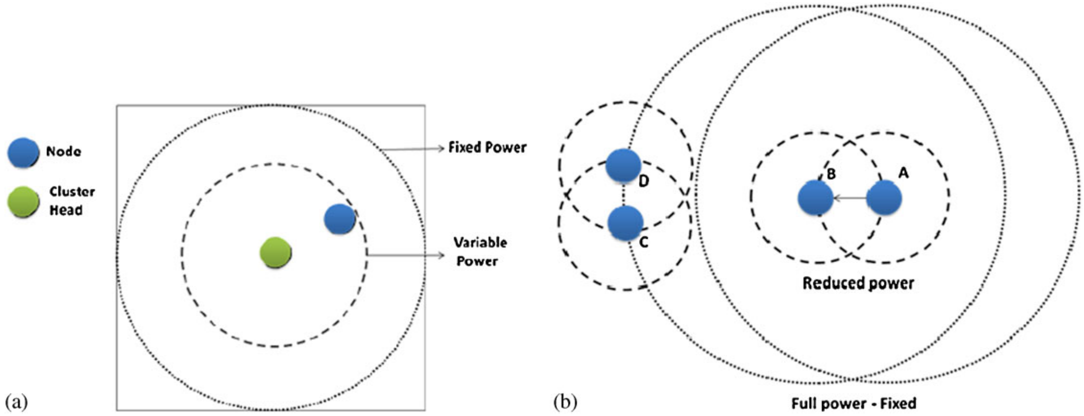

Figure 1. Variable transmission power: (a) close to cluster-head and (b) a communication scenario.

3.1.3. Inter-cluster communication. During the inter-cluster communication phase, cluster-heads send the aggregated data to their neighboring cluster-heads, which forward it to the sink. This is only possible if the cluster-heads are within the transmission range of each other. Since the nodes are mobile, during simulation it was observed that when the cluster-heads were not within the transmission range, they were unable to send the aggregated data to the sink, leading to packet loss. Packet loss during inter-cluster communication means that the aggregated data are lost, which is complete data of a specific cluster. Therefore, data of complete round are lost, which is not acceptable at all and a recovery mechanism is needed to cater to such a problem. There is no such recovery mechanism in DECA that makes it vulnerable to huge inter-cluster packet loss. Recovery mechanisms can help in reducing packet losses but the downside is the accompanied energy wastage [24]. DEMC does have a recovery mechanism to reduce inter-cluster packet loss but the scheme is not energy efficient and requires an extra cluster-head broadcast for the selection of what it refers to as *guard nodes*. As described elsewhere, guard nodes are those nodes that lie in the transmission range of multiple cluster-heads, and helps in routing. In our case we have avoided the extra broadcast of DEMC, by selecting the guard nodes during the first broadcast of the clustering message wherein nodes receiving multiple clustering messages are designated as guard nodes.

3.1.4. PCR fine tuning. With PCR, during the cluster-head selection mechanism, a node lying in the transmission range of more than one cluster-heads will select its cluster-head based on the criterion of weight, irrespective of its distance from the cluster-head. This issue may cause two problems. First, if a node resides near the border of the transmission range of a cluster-head with largest weight, then the latter will definitely become the cluster-head of the former. As the network is mobile, there is a high probability that the node will go out of transmission range of the aforementioned cluster-head. Second, the nodes associated with cluster-heads on the basis of weight, would be required to transmit with high power, resulting in energy wastage.

Considering the issues stated above we enhanced the proposed PCR protocol in order to minimize its packet loss and make it more energy efficient. The enhanced protocol is detailed in the following subsection.

3.2. The EPCR protocol

EPCR is different from PCR in terms of the selection criterion for node association with a cluster-head. In PCR, nodes are associated with the cluster-head on the basis of weight whereas in EPCR node association is done on the basis of distance.

EPCR calculates its weight and sets its timer just like PCR by utilizing Equations (1) and (2). During the initialization phase, every node assumes that it is a cluster-head and sets its cluster-head flag to true. When the timer expires for any specific node, it broadcasts a message containing its

DOI: 10.1002/dac

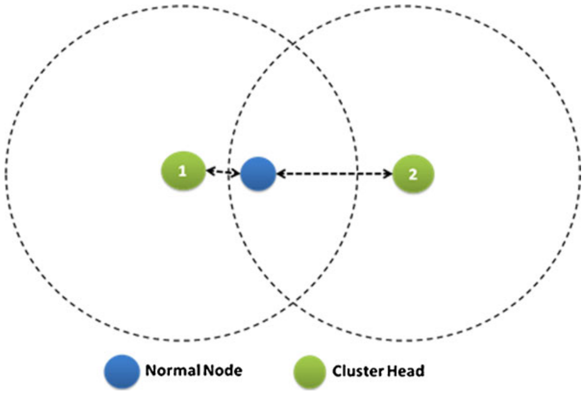

Figure 2. Node association with cluster-head.

identity to all its neighbors within its range. Only cluster-head ID is enough as, unlike PCR, there is no need of broadcasting weight to normal nodes because cluster-head selection is not based on weight. Other nodes, on receiving the clustering message, will save the received ID as cluster-head and RSSI of received message. Thereafter they will reset the cluster-head flag and cancel scheduled timer for clustering message. If the receiving node is in the range of more than one cluster-heads and second clustering message is received. The receiving node will compare previous RSSI with the new RSSI and if the latter is better then replace previous RSSI with new RSSI. In case of RSSI change, the receiving node will save the received ID as cluster-head. When the clustering phase ends, normal nodes will calculate their distance from cluster-head using Equation (3) and send their gathered information to the associated cluster-heads.

In EPCR, cluster-head selection is done on the basis of weight but nodes are associated with the cluster-heads on the basis of RSSI and not weight, which was a key limitation in the case of PCR. Associating nodes with the cluster-head on the basis of RSSI will provide two benefits. Nodes within the transmission range of two or more cluster-heads will be associated with the cluster-head that is closer to it. Hence is the first benefit, i.e. for lesser distances, lesser energy will be used in transmission of data. The second benefit of this technique is the formation of more stable clusters. As the network is mobile, for a node lying closer to cluster-head, the chance of getting out the cluster-head range is considerably lower.

For example, in Figure 2, if weight of cluster-head 2 is greater than cluster-head 1, then PCR will associate the normal node with cluster-head 2, irrespective of the fact that the node is almost on the border of cluster-head 2. For a mobile network, there is always a chance for the node to go out of the transmission range of cluster-head 2. With EPCR, however, the node will associate with cluster-head 1 because it is much closer (higher RSSI) as compared to cluster-head 2. As far as communication is concerned, both intra-cluster and inter-cluster communication of EPCR is same as those of PCR.

3.3. Recovery strategy for PCR and EPCR

There are two main approaches for packet recovery, viz. hop-by-hop and end-to-end [25]. Hop-by-hop recovery schemes have proven to be more energy efficient [26]. DEMC recovery scheme was inspired by wireless broadcast advantage (WBA) [27]. WBA was based on the fact that nodes within transmission range of sender and receiver also receive transmitted data. Therefore, these nodes should cooperate and re-transmit the data to the receiver, in case of packet loss.

Suppose (see Figure 3) during an inter-cluster communication cluster-head 1 wants to send aggregated data to cluster-head 2, which is not in the transmission range of cluster-head 1, the data will definitely be lost. Therefore, any node that lies in the transmission range of both the cluster-heads should also receive the data when cluster-head 1 is sending it to cluster-head 2. Such a node is called a *guard node* and when one or more guard nodes receive data from cluster-head 1,

DOI: 10.1002/dac

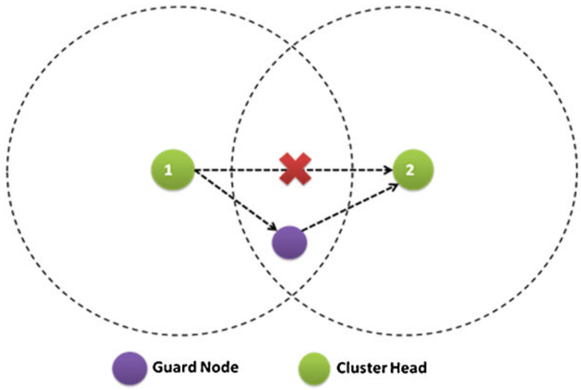

Figure 3. Recovery through guard nodes.

they wait for packet acknowledgment from cluster-head 2. If the guard nodes do not receive any acknowledgement for the sent packet, the packet is assumed to be lost. Guard nodes set timers based on residual energy just like the setting of timers for clustering. The one with greater weight will expire first and will send the received data to cluster-head 2. In this way guard nodes improve connectivity between cluster-heads and reduce packet loss. This exact mechanism is employed in DEMC [17]. The problem, however, lies in the guard node selection. For guard node selection DEMC re-broadcasts cluster message after the data are sent by normal nodes to the cluster-head.

For PCR/EPCR, we propose an enhanced recovery mechanism that does not require extra re-broadcast of the clustering message. In PCR/EPCR, the guard nodes are selected during the first broadcast of the clustering message. Nodes receiving multiple clustering messages are designated as guard nodes and help in the inter-cluster communication phase. Simulation results have shown that by reducing extra re-broadcast of the clustering message, the network lifetime can be improved. When enhanced recovery mechanism was used for PCR/EPCR, the network lifetime improved by 8–10 rounds compared to the old recovery mechanism.

4. SIMULATION RESULTS

All of the simulations were carried out using OMNET++ v4.0-based framework called INET [28]. For energy consumption, the first-order radio model, outlined in [29], was employed. According to the aforementioned model, the energy, $E_{TX}(k,d)$, required for the transmission of a k bit message over a distance of d meters, can be calculated by the following equations:

$$E_{TX}(k,d) = E_{TX} - \text{elec}(k) + E_{TX} - \text{amp}(k,d), \tag{4}$$

$$E_{TX}(k,d) = E_{\text{elec}} \times k + E_{\text{amp}} \times k \times d^2, \tag{5}$$

where E_{amp} represents the energy consumed by the amplifier to achieve an acceptable signal-to-noise ratio (SNR), whereas E_{elec} is the energy consumed by running the transceiver circuitry. The energy consumption can be calculated by the following equations:

$$E_{RX}(k) = E_{RX} - \text{elec}(k), \tag{6}$$

$$E_{RX}(k) = E_{\text{elec}} \times k, \tag{7}$$

where $E_{RX}(k)$ represents the energy required to receive a k bit message. In this simulation, the nodes employed the CSMA-CA scheme at the MAC layer and the 802.11 at the physical layer.

For the simulation, nodes were deployed randomly on the basis of the parameters outlined in Table I. PCR, DEMC, and HEED protocols were simulated with respect to different numbers of

DOI: 10.1002/dac

Table I. Simulation parameters.

Type	Parameter	Value
Network	Field dimensions	1000×1000
	Initial energy of each node	$3J$ per battery
	Location of each node	Randomly deployed
Application	Inter cluster packet size	200 bytes
	Data packet size	100 bytes
	Broadcast packet size	75 bytes
	Packet header size	25 bytes
Radio Model	E_{elec}	$50\,\mathrm{nJ/bit}$
	E_{amp}	$0.0013\,\mathrm{pJ/bit/m^4}$

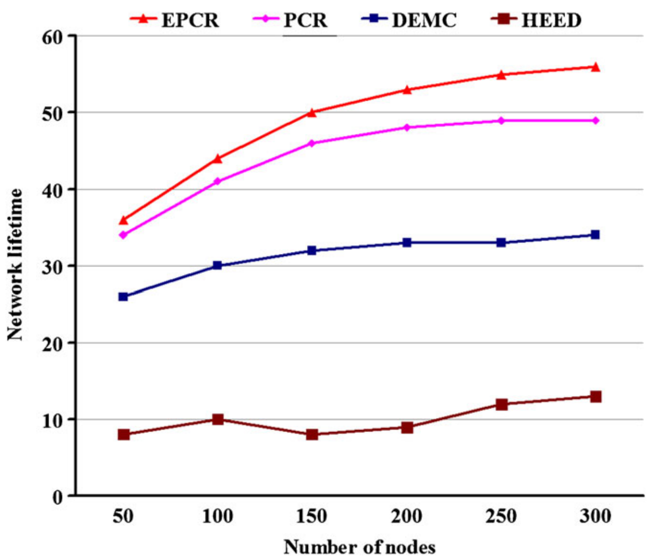

Figure 4. Network lifetime with respect to number of nodes.

nodes and at different speeds. The nodes were assumed to follow a mass mobility model [30], which is supported by the INET framework. In the mass mobility model, nodes are supposed to be having a mass and, therefore, the nodes do not start, stop or turn abruptly.

Figure 4 illustrates a trend in the network lifetime with respect to different number of nodes, with a mobility of 5 m/s for our protocols, in comparison with DEMC and HEED. It can be readily observed that the network lifetime of HEED and DEMC is low compared to PCR and EPCR. This is because HEED uses multiple clustering messages for cluster formation, which wastes energy, while DEMC uses fixed transmission power throughout the network lifetime. On the other hand, PCR uses fixed transmission power. However, the nodes change their transmission power, when they are about to send their data to the cluster-head, thus consuming lower power during the transmission of their data. The EPCR not only changes transmission power like PCR but also performs ‘smart’ clustering to save more energy. Therefore, both PCR and EPCR take advantage of the variable transmission power without disturbing the proper cluster formation. By doing this, lesser energy is consumed, leading to better network lifetime.

Because DEMC uses fixed transmission power, its network lifetime remains the same at all speeds, as can be seen in Figure 5, which plots network lifetime of 100 nodes with respect to different speeds. In contrast to DEMC, PCR and EPCR perform very well at low mobility. When the mobility is increased, the distances between nodes and cluster-heads also increase, which implies that the nodes have to transmit with higher power to get their data transmitted to cluster-head;

DOI: 10.1002/dac

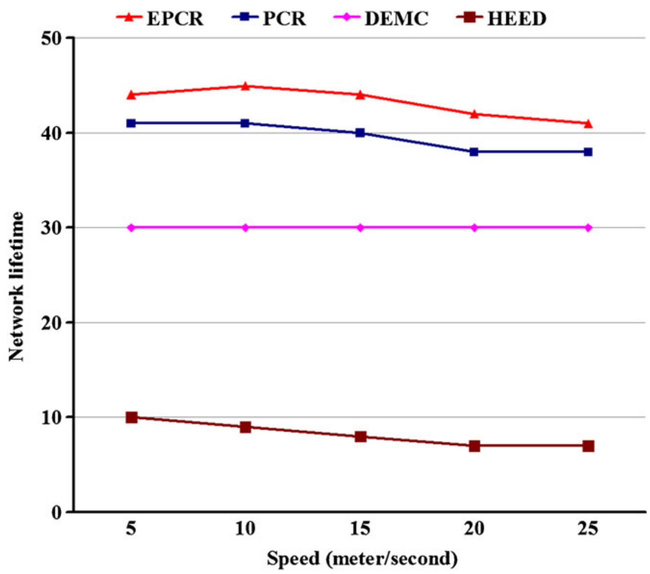

Figure 5. Network lifetime with respect to various node speeds.

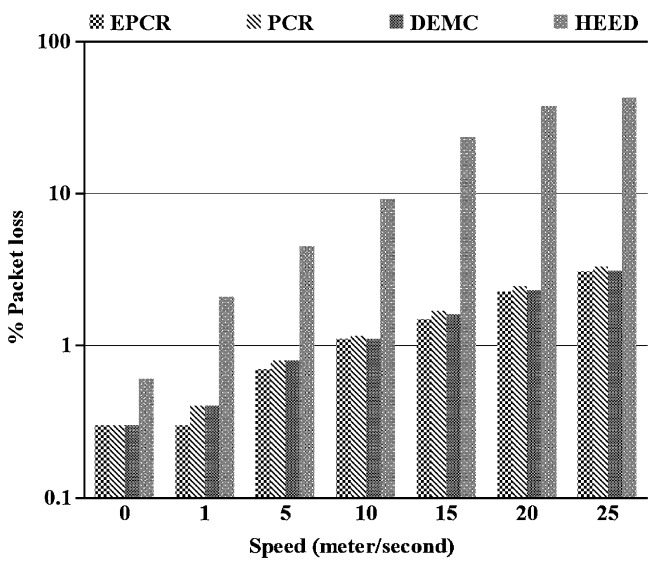

Figure 6. Packet loss with respect to different speeds.

thereby losing energy saving advantage of the variable transmission power. Despite this, they still perform far better than DEMC and HEED.

The effect of speed on the packet loss of all of the four protocols is graphically shown in Figure 6 for a network consisting of 100 nodes. One can see that, compared to HEED, there is little difference in the packet loss percentages of EPCR, PCR, and DEMC. A close look, however, suggests that although packet loss of PCR and DEMC is almost equal for lower mobility, the PCR incur elevated packet loss at higher mobilities, as compared to DEMC and EPCR. This may be attributed to the fact that reduction in the transmission power leads to packet loss increase for highly mobile networks. On the other hand, EPCR may face the same issue of packet loss because of reducing transmission power but its intelligent cluster formation nullifies the effect. For this reason, EPCR incurs less packet loss as compared to the other three protocols. HEED have the highest packet loss in comparison to PCR, EPCR, and DEMC because it has no support for

DOI: 10.1002/dac

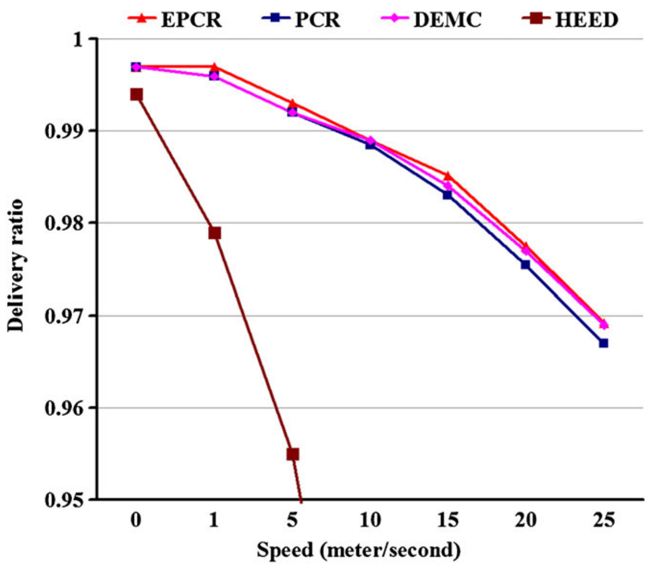

Figure 7. Packet delivery ratios with respect to different speeds.

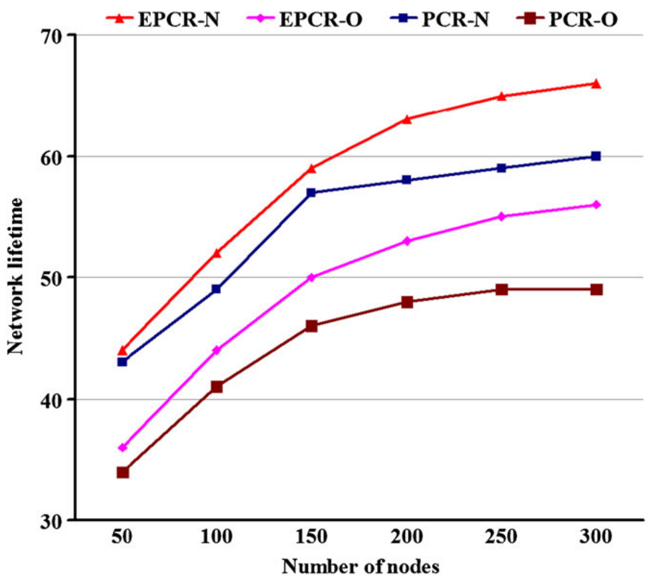

Figure 8. PCR and EPCR network lifetime with enhanced recovery mechanism.

mobility, no recovery mechanism and it exchanges multiple messages for cluster-head formation. Another manner, to highlight the facts above, is illustrated in the form of Figure 7, which represents the delivery ratio of all protocols as a function of speed. For obvious reasons, EPCR has high packet delivery ratio compared to the other three protocols.

The advantage of the recovery mechanism, outlined elsewhere, is highlighted in Figure 8 which plots the network lifetime as a function of the number of nodes. In the aforementioned figure, the series PCR-O and EPCR-O employ the recovery mechanism of DEMC and performs extra broadcast for the selection of guard nodes while the PCR-N and ECPR-N use our proposed enhanced recovery mechanism that does not require extra broadcast for the selection of guard nodes. It can be seen that the versions eliminating extra communication, i.e. PCR-N and EPCR-N, give better network lifetime compared to PCR-O and EPCR-O.

DOI: 10.1002/dac

5. CONCLUSION

Two WSN-oriented protocols were presented in this paper with the aim to encompass both static and mobile networks. Simulation-based comparison of the proposed protocols was carried out with DEMC and HEED which showed interesting results. The PCR is supposed to be more energy efficient as compared to many clustering protocols and this energy efficiency maximized the network lifetime when variable transmission power was employed and the recovery mechanism was enhanced. EPCR is an extension of PCR in which the packet delivery ratio and network lifetime was improved by efficiently associating nodes with cluster-head. Our proposed protocols are more energy efficient, provide high packet delivery ratio and rely on an efficient recovery mechanism.

During the simulation of both the proposed protocols, the first-order radio model was used along with the linear battery consumption model, which is quite simple. In the near future, it is our endeavor to simulate the proposed protocols using a second-order radio model along with some detailed energy consumption model to get more realistic results. Moreover, these protocols will be simulated with respect to different mobility models to check their ultimate performance under different environments. Last but not the least, there is a need to come up with optimal values for different mobility parameters where the recovery strategy of PCR/EPCR outperforms other related recovery mechanisms.

REFERENCES

1. Monks JP, Bharghavan V, Hwu W-MW. A power controlled multiple access protocol for wireless packet networks. *Proceedings of the IEEE INFOCOM 2001*, *Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies*, Anchorage, AK, U.S.A., 2001; 219–228.
2. Muqattash A, Krunz M. Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks. *Proceedings of the IEEE INFOCOM 2003*, *Twenty-second Annual Joint Conference of the IEEE Computer and Communications Societies*, San Francisco, CA, U.S.A., 2003; 470–480.
3. Narayanaswamy S, Kawadia V, Sreenivas RS, Kumar PR. Power control in ad-hoc networks: theory, architecture, algorithm and implementation of the COMPOW protocol. *Proceedings of the European Wireless Conference*, Florence, Italy, 2002; 156–162.
4. Gomez J, Campbell AT, Naghshineh M, Bisdikian C. PARO: supporting dynamic power controlled routing in wireless ad hoc networks. *ACM/Kluwer Journal on Wireless Networks* 2003; **9**:443–460.
5. Jung ES, Vaidya NH. A power control MAC protocol for ad hoc networks. *ACM/Kluwer Journal on Wireless Networks* 2005; **11**:55–66.
6. Abusaimeh H, Yang SH. Reducing the transmission and reception powers in the AODV. *Proceedings of the ICNSC '09*, *International Conference on Networking*, *Sensing and Control*, Okayama City, Japan, 2009; 60–65.
7. Hoang AT, Motani M. Collaborative broadcasting and compression in cluster-based wireless sensor networks. *ACM Transactions on Sensor Networks* 2007; **3**(17):1–34.
8. Younis M, Youssef M, Arisha K. Energy-aware routing in cluster-based sensor networks. *Proceedings of the MASCOTS '02*, *The 10th IEEE International Symposium on Modeling*, *Analysis*, *and Simulation of Computer and Telecommunications Systems*, Washington, DC, U.S.A. IEEE Computer Society, 2002; 129–136.
9. Buczak VR, Jamalabad AL. Self-organization of a heterogeneous sensor network by genetic algorithms. *Engineering Systems Through Artificial Neural Networks* 1998; **8**:259–264.
10. Lin CR, Gerla M. Adaptive clustering for mobile wireless networks. *IEEE Journal on Selected Areas in Communications* 1997; **15**(7):1265–1275.
11. Lindsey S, Raghavendra CS. PEGASIS: Power-efficient gathering in sensor information systems. *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, U.S.A., vol. 3, 2002; 1125–1130.
12. Madani S, Weber D, Mahlknecht S. Position-based routing protocol for low power wireless sensor networks. *Journal of Universal Computer Science* 2010; **16**(9):1215–1233.
13. Ye M, Li CF, Chen GH, Wu J. EECS: an energy efficient clustering scheme in wireless sensor networks. *Proceedings of the Second IEEE International Performance Computing and Communications Conference* (*IPCCC*), Phoenix, AZ, U.S.A., 2005; 535–540.
14. Li CF, Ye M, Chen GH, Wu J. An energy-efficient unequal clustering mechanism for wireless sensor networks. *Proceedings of the Second IEEE International Conference on Mobile Adhoc and Sensor Systems* (*MASS*), Washington, DC, 2005.
15. Younis O, Fahmy S. HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. *IEEE Transactions on Mobile Computing* 2004; **3**(4):366–379.

16. Yu M, Li JH, Levy R. Mobility resistant clustering in multi-hop wireless networks. *Journal of Networks* 2006; **1**(1):12–19.
17. Ali S, Madani S. Distributed efficient multihop clustering protocol for mobile sensor networks. *The International Arab Journal of Information Technology* 2011; **8**(3):302–309.
18. Max S, Wang T. Transmit power control in wireless mesh networks considered harmful. *Proceedings of MESH 2009*, *Second International Conference on Advances in Mesh Networks*, Athens/Glyfada, Greece, June 2009; 73–78.
19. Lau EEL, Lee BG, Lee SC, Chung WY. Enhanced RSSI-based high accuracy real-time user location tracking system for indoor and outdoor environments. *International Journal on Smart Sensing and Intelligent Systems* 2008; **1**(2):12–19.
20. Mao G, Fidan B, Anderson BDO. Wireless sensor network localization techniques. *Computer Networks* 2007; **51**:2529–2553.
21. Barsocchi P, Lenzi S, Chessa S, Giunta G. Virtual calibration for RSSI-based indoor localization with IEEE 802.15.4. *Proceedings of ICC '09*, *The IEEE International Conference on Communications*, Dresden, Germany, 2009; 1–5.
22. Jeong S, Oh C. RSSI-based cooperative localization algorithm using virtual reference nodes. *Proceedings of NetApps2008*, *International Conference on Network Applications*, *Protocols and Services*, Utara, Malayasia, 2008.
23. Chen W, Meng X. A cooperative localization scheme for Zigbee-based wireless sensor networks. *Proceedings of the 14th IEEE International Conference* (*ICON '06*), Big Sky, MT, U.S.A., vol. 2, 2006; 1–5.
24. Rehman A, Ali S, Mustafa S, Madani SA. Behavior of clustering based routing protocols with respect to different mobility models in mobile WSNs. *International Conference on Intelligence and Information Technology*, Lahore, Pakistan, 2010.
25. Yick J, Mukherjee B, Ghosal D. Wireless sensor network survey. *Computer Networks* 2008; **52**:2292–2330.
26. Stann F, Heidemann J. RMST: reliable data transport in sensor networks. *Proceedings of the First IEEE International Workshop on Sensor Network Protocols and Applications*, Anchorage, AK, U.S.A., 2003; 102–112.
27. Wieselthier JE, Nguyen GD, Ephremides A. Algorithms for energy-efficient multicasting in ad hoc wireless networks. *Mobile Networks and Applications* 2001; **6**:251–263.
28. Varga A. The OMNeT++ discrete event simulation system. *Proceedings of the ESM 2001*, *European Simulation Multiconference*, Prague, Czech Republic, 2001.
29. Heinzelman WR, Chandrakasan A, Balakrishnan H. Energy-efficient communication protocol for wireless microsensor networks. *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, Maui, HI, U.S.A., vol. 2, 2000; 10.
30. Drytkiewicz W, Sroka S, Handziski VH, Kopke A, Karl H. A mobility framework for OMNeT++ 2003. URL http://www.tkn.tu-berlin.de/publications/papers/mobility_framework.pdf.

AUTHORS' BIOGRAPHIES

Atta ur Rehman Khan received BS degree in computer science from COMSATS Institute of Information Technology (CIIT) Abbottabad, Pakistan, in 2007. In 2007 he founded DeeByte software solutions and became the first CEO of that firm. He joined CIIT again in 2008 as a research associate and received MS degree with specialization in wireless networks from the same institute in 2010. Since then he is working as a full time lecturer in the institute and is the secretary of COMSATS Wireless Research Group (CWRG). His area of interest is ubiquitous networks.

Sajjad A. Madani joined CIIT in August 2008 as Assistant Professor. Before that, he worked as a guest research scholar at the Institute of Computer Technology (ICT), Vienna University of Technology, Austria. Prior to joining ICT, he taught at CIIT, Abbottabad, for a period of two years as a lecturer. He has done MS in Computer Sciences from Lahore University of Management Sciences (LUMS), Pakistan, with excellent academic standing and BSc Civil Engineering from UET, Peshawar, and was awarded a gold medal for his outstanding performance in academics. He has over 20 publications in international journals and conferences to his credit. He is currently working on cross layer optimization of power aware wireless sensor networks as well as application of industrial informatics to electrical energy networks.

DOI: 10.1002/dac

Khizar Hayat received his PhD degree in June 2009 from the University of Montpellier II (UM2), France, while working at the Laboratory of Informatics, Robotics and Microelectronics Montpellier (LIRMM). Since December 2009, he is with the Computer Sciences Department of CIIT Abbottabad, Pakistan, as Assistant Professor. He is the convener of the research group 'Information Security and Image Processing (ISIP)' at CIIT. His areas of interest are image processing and information security.

Samee U. Khan received a BS degree from Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Swabi, Pakistan, in May 1999, and a PhD degree from the University of Texas, Arlington, TX, U.S.A., in August 2007. Currently, he is Assistant Professor of Electrical and Computer Engineering at the North Dakota State University, Fargo, ND, U.S.A. He is the founding director of bi-institutional and multi-departmental NDSU-CIIT Green Computing and Communications Laboratory (GCC Lab). The GCC Lab currently hosts 10 faculty members and over 35 research students. Moreover, he is Adjunct Professor of Computer Science and Operations Research at the North Dakota State University, Fargo, ND, U.S.A. Furthermore, he also is an Adjunct Professor of Computer Science, COMSATS Institute of Information Technology, Pakistan.

DOI: 10.1002/dac